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Waterways Experiment  
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# **Methods of Preparing Horizontal Construction Joints in Mass Concrete**

## **Report 2 Minimizing Laitance**

*by Billy D. Neeley, Toy S. Poole, Charles A. Weiss, Jr.*

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by Billy D. Neeley, Toy S. Poole, Charles A. Weiss, Jr.

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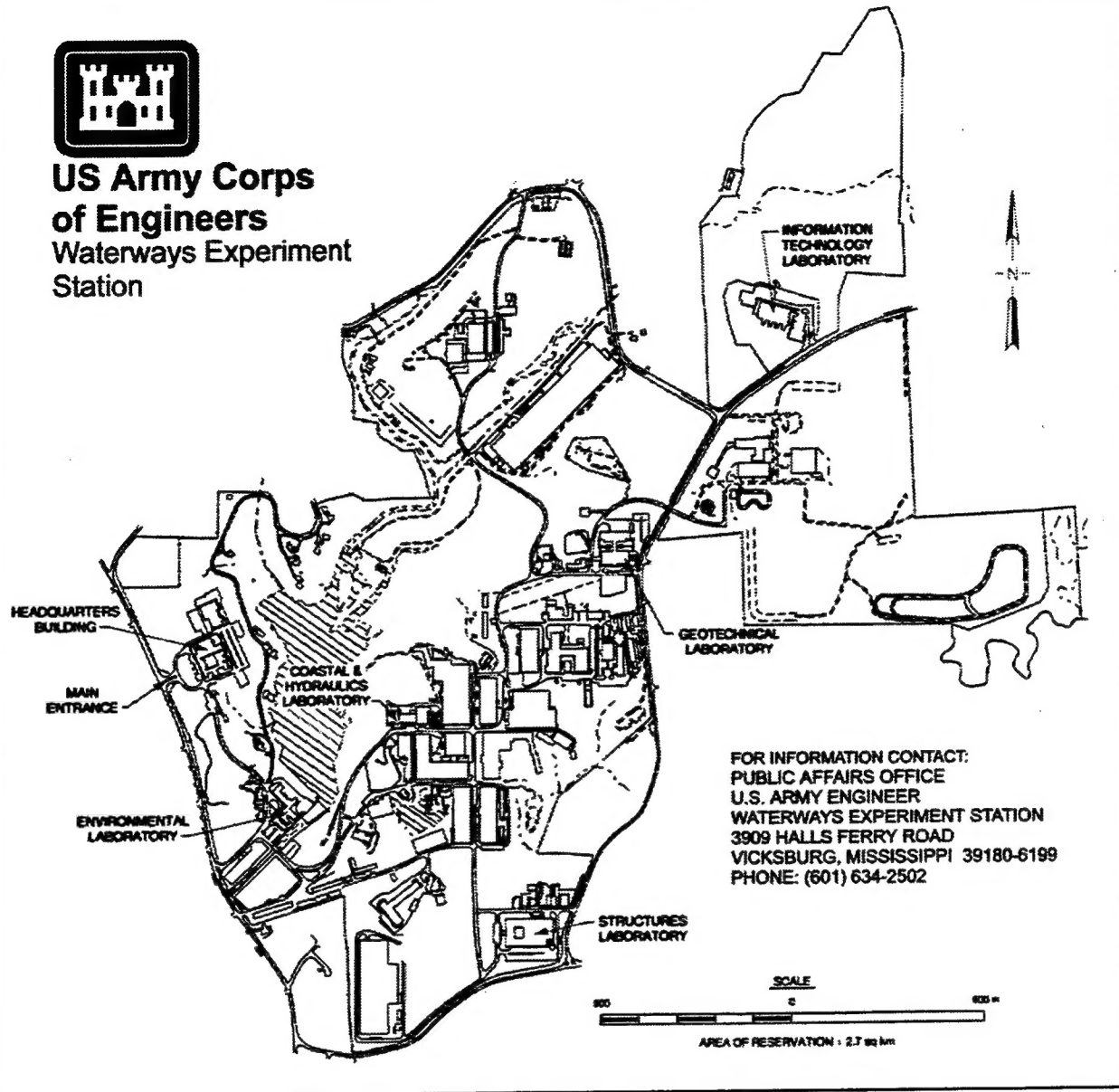
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# Preface

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The investigation described in this report was conducted by the Concrete and Materials Division (CMD), Structures Laboratory (SL), U.S. Army Engineer Waterways Experiment Station (WES). The work was sponsored by Headquarters, U.S. Army Corps of Engineers, as a part of Civil Works Investigation Studies Work Unit 32767, "Horizontal Construction Joint Treatment in Mass Concrete."

The study was conducted under the general supervision of Messrs. Bryant Mather, Director, SL, and John Q. Ehrgott, Assistant Director, SL, and Dr. Paul F. Mlakar, Chief, CMD. Direct supervision was provided by Mr. Edward F. O'Neil, Acting Chief, Engineering Mechanics Branch (EMB), CMD. Mr. Billy D. Neeley, EMB, was the Principal Investigator and coauthored this report with Drs. Toy S. Poole and Charles A. Weiss, Jr., Engineering Sciences Branch, CMD. Messrs. Michael Lloyd, Jimmy Hall, Cliff Gill, and Michael Hedrick and Ms. Linda Mayfield, EMB, assisted in preparing and testing the concrete specimens.

At the time of publication of this report, Director of WES was Dr. Robert W. Whalin. Commander was COL Robin A. Cababa, EN.

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# 1 Introduction

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## Background

Under ideal conditions, any mass concrete structure should be monolithic. However, mass concrete structures usually contain horizontal construction joints because it is impractical to place such a large volume of concrete without lengthy interruptions. These joints must be capable of transmitting stress combinations, including tension, compression, and horizontal shear, from one part of the concrete structure to another. As a minimum, a horizontal construction joint must have bond, tensile, and shear strengths greater than the stresses to which it will be subjected. Ideally, the strength of the joint should be equal to that of the surrounding concrete.

Planes of weakness can result if horizontal construction joints are not prepared properly during construction. Structural weakness, leakage, and subsequent deterioration can result from a poorly prepared horizontal construction joint. The quality of a horizontal construction joint in mass concrete depends on both the quality of the concrete, both above and below the joint, and the preparation of the joint surface.

Experience has shown that the lower surface of a joint plane must be cleaned thoroughly prior to placement of fresh concrete to ensure good bond strength and watertightness of the two layers. Various methods of cleaning the lower surface of a joint plane have been used. Civil Works Guide Specification CWGS-03305, "Mass Concrete" (Headquarters, Department of the Army 1992), has provisions for cleaning by air-water cutting, high-pressure water jet, or wet sandblasting. It states that all laitance and inferior concrete should be removed so that clean, well-bonded coarse aggregate particles are exposed over the lift surface. However, the coarse aggregate particles should not be undercut. Use of a surface retarder is permitted to extend the period of time during which air-water cutting is effective. CWGS-03305 also states that the surface of a construction joint should be kept continuously wet for the first 12 hr of the 24-hr period prior to placing the fresh concrete, except that the surface shall be damp with no free water at the time of placement.

Between 1959 and 1973, four technical reports were published by the U.S. Army Engineer Waterways Experiment Station (WES) describing the results of an investigation of methods of preparing horizontal construction joints (Tynes 1959; Tynes 1963; McDonald and Smith 1966; Tynes and McCleese 1973). These investigations generally concluded that (a) wet sandblasting, air-water cutting, and high-pressure water jetting were effective methods of cleaning a joint surface, (b) application of mortar to a joint surface did not improve the integrity of the joint, and (c) a stronger and more impermeable joint will result if the hardened concrete surface is dry when the fresh concrete is placed. Pacelli, Andriolo, and Sarkaria (1993) presented case histories of investigations regarding the performance of construction joints in five large concrete dams. Test results indicating the bond and shear strengths of new concrete placed on the cleaned and roughened surface of existing concrete were presented. Their investigations generally concluded that (a) high-pressure water jetting and air-water cutting were as effective as wet sandblasting for cleaning a joint surface, (b) properly prepared construction joints had shear and tensile strengths equal to at least 85 percent of that of the intact concrete, (c) roughness of the joint surface did not have a significant influence on the strength of the joint, (d) application of mortar to a joint improved the joint strength only if the joint surface was not properly cleaned, and (e) the permeability of a properly prepared joint was essentially the same as that of the intact concrete. Neeley and Poole (1996) concluded that (a) the surface was adequately cleaned when the visible laitance had been removed and fine and coarse aggregate particles had been exposed, (b) undercutting the coarse aggregate particles was unnecessary, and (c) allowing the joint surface to dry approximately 24 hr prior to placement of the next lift and placing on the dry surface would result in a stronger joint.

In light of the conclusions cited above, a new question arose. If surface cleanliness and moisture content are more important than surface roughness (degree of aggregate interlock created by undercutting the coarse aggregate particles), could an adequately prepared joint surface be produced without using cleaning procedures such as high-pressure water jetting, air-water cutting, or sandblasting? Or more simply stated, if loose surface laitance could be prevented or minimized, would surface cleaning still be required? To answer this question, methods to minimize laitance needed to be examined.

Laitance is defined by the American Concrete Institute (ACI) Committee 116 (ACI 1997) as "a layer of weak and nondurable material containing cement and fines from aggregates, brought by bleeding water to the top of overwet concrete; the amount is generally increased by overworking or overmanipulating concrete at the surface by improper finishing or by job-traffic." ACI Committee 116 (ACI 1997) defines bleeding as "the autogenous flow of mixing water within, or its emergence from, newly placed concrete or mortar; caused by the settlement of the solid materials within the mass." Generally, most normal strength concrete mixtures are mixed using more water for workability than is needed in the mixture to fill the space among the solid particles of aggregate and cement. These particles are initially suspended in

this water. After concrete has been placed but before the cement has stiffened, some settling of aggregate and cementitious material particles occurs. As the settlement occurs, some of the excess mixing water is released. The released water, being the lightest component, then migrates (bleeds) to the top surface of the concrete. A nominal amount of bleeding is common for most concretes and, if handled properly, is not necessarily bad. However, in some instances a scum of fine particles can be carried to the surface by the bleed water. These particles can create a weak, nondurable surface. In some cases calcium hydroxide can precipitate from solution in the bleed water and can react with  $\text{CO}_2$  in the air at the surface, leading to the formation of  $\text{CaCO}_3$ . After eventual evaporation of the bleed water, the fine particles can be seen as a dusting or flaking of loose material on the surface, or in the case of  $\text{CaCO}_3$ , a white powdery material. This laitance, if not removed, can act as a bond breaker.

Since laitance is the result of bleeding, it follows that reducing bleeding should reduce laitance. Mindess and Young (1981) list four ways to reduce bleeding: (a) increase fineness of the cement (portland cement or ground granulated blast-furnace slag) or add pozzolans or other finely divided mineral admixtures, (b) increase the rate of hydration of the cement by using cements with high alkali contents or high  $\text{C}_3\text{A}$  contents, or use  $\text{CaCl}_2$  as an admixture, (c) use air entrainment, and (d) reduce the water content. Use of high alkali, high  $\text{C}_3\text{A}$ , or finely ground cement, and  $\text{CaCl}_2$  is not desirable in mass concrete. In most instances, use of such materials would not be permitted. Use of  $\text{CaCl}_2$  is not permitted in most Corps concrete. When an accelerating admixture is allowed, usually only nonchloride materials may be used. Most concrete used by the Corps has entrained air. Water content is minimized by careful mixture proportioning and effective use of water-reducing admixtures. Pozzolans, such as fly ash, or ground granulated blast-furnace slag are used in nearly all Corps mass concrete.

It can be concluded that efforts to reduce bleeding are already incorporated into the proportioning of Corps mass concrete. The purpose of this research effort was to determine if bleeding could be minimized further through use of other pozzolans or chemical admixtures. Pozzolans such as silica fume have a much higher water demand than does fly ash. One characteristic of silica fume concretes is that bleeding is either minimal or nonexistent. Silica fume is normally used to produce high-strength or highly impermeable concrete. While neither of these two attributes is needed for typical mass concrete, it is possible that a small addition of silica fume to the total cementitious material could significantly reduce bleeding without significantly affecting other fresh and hardened properties. Another possible solution is with the addition of a chemical admixture, antiwashout admixture (AWA). AWAs are normally used to increase the cohesiveness of concrete to be placed underwater, thus minimizing washout of the cementitious paste from the aggregate particles. Another result is that bleeding is reduced. Therefore, it is possible that a small addition of an AWA to the mass concrete mixture could significantly reduce bleeding without significantly affecting other fresh and hardened properties.

## Objectives

The objectives of this research program were as follows:

- a.* Determine if loose, flaky laitance could be minimized, or prevented, on the surface of a mass concrete placement.
- b.* Determine the strength of a horizontal construction joint where bleeding had been minimized and surface cleaning had not been used.

## Scope

Mass concrete monolithic models similar to those used in the earlier investigations were constructed. An addition of 2.5 percent of silica fume, by volume of cementitious material, was chosen as the method to minimize bleeding. Three surface moisture conditions were evaluated. Properties tested were direct tensile strength and shear strength of the joint. Drying shrinkage of the concrete was also measured to evaluate the effect of the silica fume on the shrinkage properties of the concrete. A test matrix is given in Table 1. After property measurements on concrete from the monolithic models had been completed, a second small experiment was executed in an attempt to determine the cause of some unexpected results. Many of the measurements were made and recorded in non-SI units and converted to SI units using conversion values in American Society for Testing and Materials (ASTM) E 380 (ASTM 1996o).

Table 1 Test Matrix		
Block Identifier	Type of Joint Preparation	Moisture Condition of Joint
M	None	Wet continuously.
N	None	Wet continuously, then dry 16 hr prior to placement, then moisten surface immediately before placement.
O	None	Dry 24 hr before placement.

## 2 Experimental Program

---

### General

The materials and concrete mixtures used in this investigation were typical of those currently used in mass concrete construction. A brief description of the materials, mixtures, and test specimens is given below.

### Materials and Mixtures

#### Materials

The coarse aggregate was 75-mm nominal-maximum-size (NMS) crushed limestone. The fine aggregate was a natural sand. The grading (ASTM C 136 (ASTM 1996e)) of each aggregate and values of absorption and specific gravity (ASTM C 127 (coarse aggregate) and C 128 (fine aggregate) (ASTM 1996c,d)) are given in Table 2. A graph showing grading of the coarse aggregate is shown as Figure 1.

The cement was portland cement, conforming to Type II requirements of ASTM C 150 (ASTM 1996h). The fly ash conformed to Class F requirements of ASTM C 618 (ASTM 1996m). The silica fume conformed to the requirements of ASTM C 1240 (ASTM 1996n). Physical and chemical properties of the cement, fly ash, and silica fume are given in Tables 3, 4, and 5, respectively.

#### Mixtures

The concrete mixtures were proportioned in accordance with ACI 211.1, "Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete" (ACI 1996). The mortar content for the mixtures was within the range recommended by ACI 211.1 for concrete mixtures containing 75-mm NMS aggregate. The combined grading of the coarse aggregate is given in Figure 1. The total cementitious material in the mixture without silica fume

Table 2 Aggregate				
Sieve Size	Cumulative Percent Passing			
	75-mm NMS Coarse Agg.	37.5-mm NMS Coarse Agg.	19.0-mm NMS Coarse Agg.	Fine Agg.
75 mm	100			
50 mm	50	100		
37.5 mm	8	96		
25.0 mm	1	29	100	
19.0 mm		7	97	
12.5 mm		3	65	
9.5 mm		3	39	
4.75 mm		2	6	100
2.36 mm			1	80
1.18 mm				68
600 $\mu\text{m}$				57
300 $\mu\text{m}$				23
150 $\mu\text{m}$				2
Specific Gravity	2.65	2.74	2.71	2.60
Absorption, %	1.6	0.3	0.2	1.2
CMD ID	950122	CL-2 MG-2	920048	950057

Table 3 Portland Cement			
Property, %	Result	CMD ID 920044	
		Property	Result
SiO <sub>2</sub>	21.4	C <sub>3</sub> A, %	6
Al <sub>2</sub> O <sub>3</sub>	3.4	C <sub>3</sub> S, %	61
Fe <sub>2</sub> O <sub>3</sub>	2.4	C <sub>2</sub> S, %	16
CaO	63.7	C <sub>4</sub> AF, %	7
MgO	3.8	Heat of hydration, kJ/kg	305
SO <sub>3</sub>	2.8	Surface area, m <sup>2</sup> /kg	371
Loss on ignition	1.1	Autoclave expansion, %	0.08
Insoluble residue	0.06	Initial set (Gillmore), min	165
Na <sub>2</sub> O	0.18	Final set (Gillmore), min	265
K <sub>2</sub> O	0.74	Air content, %	9
Alkalies - total as Na <sub>2</sub> O	0.67	Compressive strength, 3 days, MPa	21.8
TiO <sub>2</sub>	0.15	Compressive strength, 7 days, MPa	28.1
P <sub>2</sub> O <sub>5</sub>	0.10	False set	88

Table 4 Fly Ash			
Property, %	Result	CMD ID 930028	
		Property	Result
SiO <sub>2</sub>	53.9	Loss on ignition, %	1.6
Al <sub>2</sub> O <sub>3</sub>	27.1	Available alkalies, %	0.9
Fe <sub>2</sub> O <sub>3</sub>	11.0	Fineness, residue 45- $\mu$ m sieve, %	15
Sum SiO <sub>2</sub> , Al <sub>2</sub> O <sub>3</sub> , Fe <sub>2</sub> O <sub>3</sub>	91.9	Water requirement, %	97
MgO	0.9	Density, Mg/m <sup>3</sup>	2.36
SO <sub>3</sub>	0.3	Autoclave expansion, %	-0.06
Moisture content	0.2	Pozzolanic activity with lime, MPa	7.9
		Strength activity with cement, %	86

Table 5 Silica Fume			
Property, %	Result	CMD ID 950570	
		Property	Result
SiO <sub>2</sub>	85.9	Density, Mg/m <sup>2</sup>	2.24
Moisture content	0.3	Surface area, m <sup>2</sup> /kg	3,740
Loss on ignition	0.1		

was 60 percent portland cement and 40 percent fly ash by volume. The total cementitious material in the mixture with silica fume was 58.5-percent portland cement, 39-percent fly ash, and 2.5-percent silica fume by volume. The concrete mixture proportions are given in Table 6. Tests were conducted on the fresh concrete to determine slump (ASTM C 143) (ASTM 1996g), unit weight (ASTM C 138) (ASTM 1996f), and air content (ASTM C 231) (ASTM 1996k). Cylindrical specimens (152-mm diam by 305-mm high) were prepared according to ASTM C 192 (ASTM 1996j) and cured in a moist curing room meeting the requirements of ASTM C 511 (ASTM 1996l) until time of testing. Specimens were tested in unconfined compression at 7-, 14-, 28-, and 90-day age according to ASTM C 39 (ASTM 1996a). Results of tests on the unhardened concrete and the unconfined compression tests are given in Table 7. Unrestrained prisms (76- by 76- by 254-mm) were prepared and cured according to ASTM C 157 (ASTM 1996i) for determination of drying shrinkage.

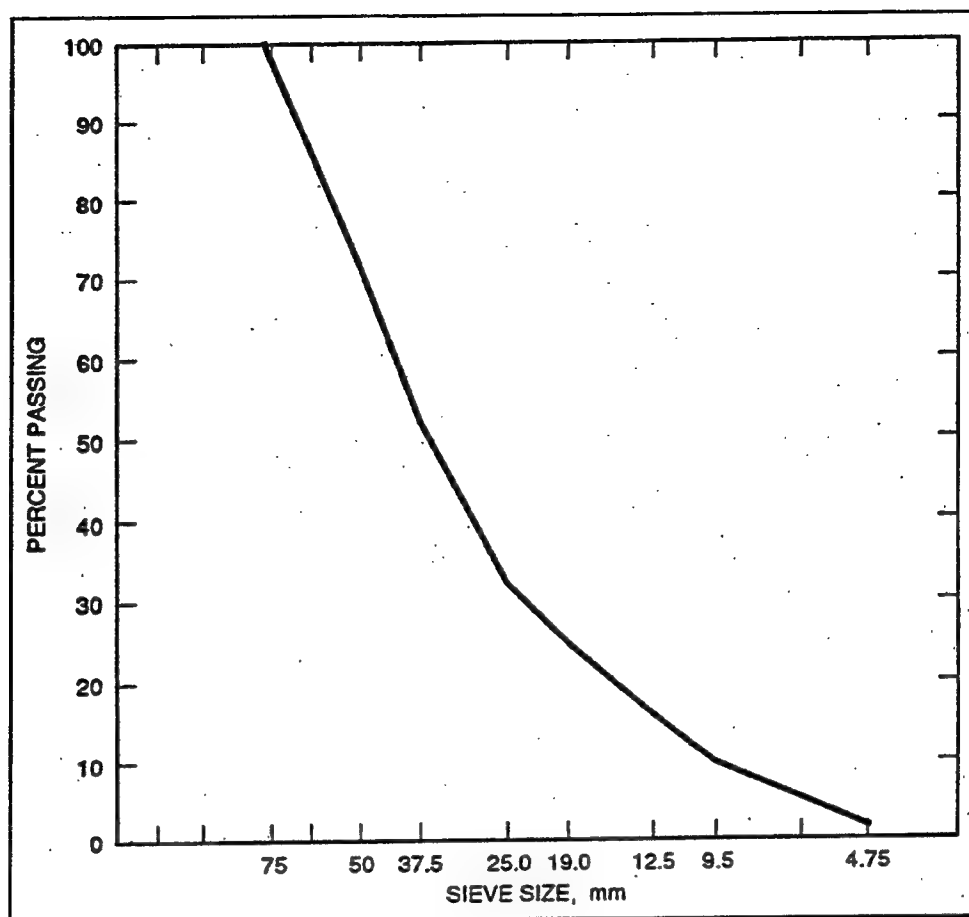


Figure 1. Combined grading of coarse aggregate

## Test Blocks

The three moisture conditions described in the experimental program were each represented by a single test block of concrete, designated M, N, and O, as shown in Table 1. Each block was 0.92 m long, 0.53 m wide, and 0.75 m high and was cast in two lifts. The first lift was 0.45 m deep and incorporated silica fume as 2.5 percent of the total cementitious material. The surface of the fresh concrete was not finished. Block M (continuously wet) was cured with wet burlap and sheet plastic for 14 days, after which the covering was removed. The surface was vacuumed to remove loose particles, and the second lift (0.3 m thick) was placed. Block N (dry then rewet) was cured with burlap and sheet plastic for 13 days, after which the surface was allowed to dry for 16 hr. The surface was then remoistened and vacuumed, and the second lift (0.3 m thick) was placed. Block O (dry) was cured with the burlap and plastic for 13 days, after which the surface was allowed to dry for 24 hr. The surface was vacuumed, and the second lift (0.3 m thick) was placed. Photographs of the concrete surfaces as prepared are shown in Figures A1 through A6 in Appendix A.



**Table 6**  
**Concrete Mixture Proportions**

Material	1 cubic metre	
	Mass, kg	Volume, m <sup>3</sup>
<b>Mixture without Silica Fume</b>		
Portland	109	0.035
Fly ash	55	0.023
Fine aggregate	635	0.244
19.0-mm NMS coarse aggregate	362	0.134
37.5-mm NMS coarse aggregate	381	0.139
75-mm NMS coarse aggregate	752	0.284
Water	100	0.100
Air-entraining admixture	0.19 L	
<b>Mixture with Silica Fume</b>		
Portland cement	109	0.035
Fly ash	55	0.023
Silica fume	3	0.001
Fine aggregate	634	0.244
19.0-mm NMS coarse aggregate	361	0.133
37.5-mm NMS coarse aggregate	380	0.139
75-mm NMS coarse aggregate	750	0.283
Water	101	0.101
Air-entraining admixture	0.19 L	

**Table 7**  
**Test Results, Fresh and Hardened Concrete<sup>1</sup>**

Test Blocks	Layer <sup>2</sup>	Slump mm	Air Content <sup>3</sup> %	Compressive Strength, MPa
				90 day
M,N,O	Bottom	40	5.3	23.0
	Top	20	5.1	20.9

<sup>1</sup> Average of two batches for each layer.

<sup>2</sup> Bottom - concrete with silica fume; top - concrete without silica fume.

<sup>3</sup> In that portion of the concrete containing aggregate smaller than the 37.5-mm sieve.

## Tests and Preparation of Test Specimens

A minimum of twelve 152-mm-diam cores were taken from each test block using a diamond-bit core barrel, according to ASTM C 42 (ASTM 1996b). Cores were cut perpendicular to the horizontal joint, completely through the test block, as shown in Figure 2. Cores were randomly selected for direct tensile testing or shear testing. Test specimens were then cut from the cores as illustrated in Figure 3. The experimental design required six intact specimens and six specimens with joints for direct-tensile strength testing according to CRD-C 164 (WES 1949), six intact specimens and six specimens with joints for shear-strength testing according to RTH-203 (WES 1989), and six intact specimens for compressive-strength testing according to ASTM C 42 (ASTM 1996b). Shear strength was measured at three levels of normal loading. Nominal values of normal stress were 192, 383, and 766 kPa, although actual values were recorded. Two specimens were tested at each level of normal load to determine the maximum shear strength at failure of the joint plane. A linear regression line was calculated with normal stress as the independent variable (X) and measured shear strength as the dependent variable (Y). The Y intercept (shear at zero normal loading) was taken as the cohesion. The standard error of the intercept was used to compare results among treatment conditions. The coefficient of internal friction,  $\phi$ , is the arctan of the slope of the regression line. The standard error of the slope was used for statistical evaluations of  $\phi$ . After maximum shear determinations had been completed, shear testing was repeated on the broken specimens to determine the residual values of cohesion and  $\phi$ . Residual values of cohesion and  $\phi$  were calculated by the same linear regression procedure as for maximum shear strength.

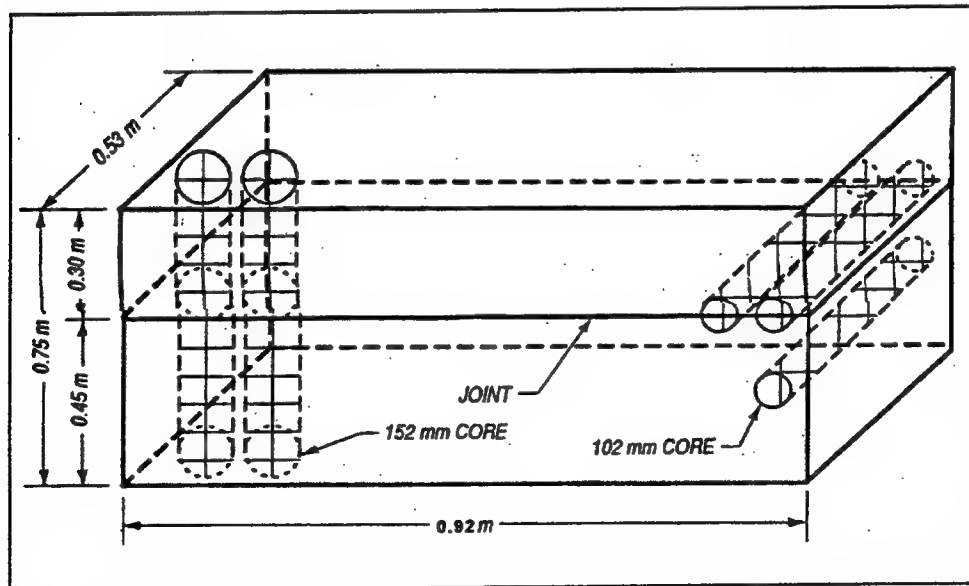


Figure 2. Test article

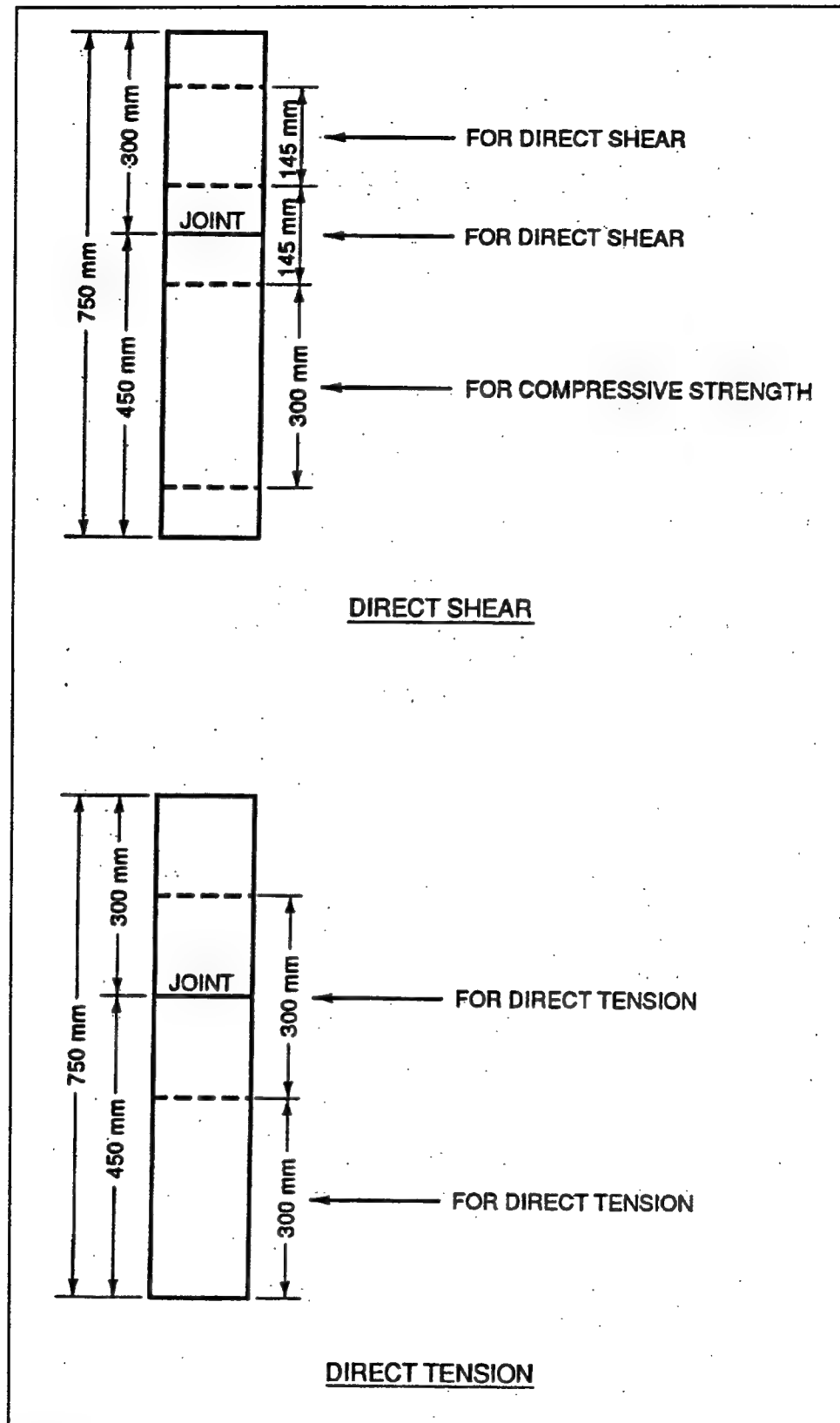


Figure 3. Preparation of cores

Numbers of specimens actually tested for each property differed from the number in the experimental design because some were broken during drilling or sawing. Actual numbers tested are indicated in the tabulation of results.

## **Effect of Curing on Concrete Mineralogy**

### **Fabrication of samples for X-ray diffraction analysis**

To ascertain if the hydration of the cement phases aided in the ability to obtain a good bond on the lift surface between the subsequent lifts of concrete, a series of samples were fabricated. In this experiment, only the first lift was placed. The concrete mixtures (with and without 2.5-percent silica fume by volume of total cementitious material) were the same as were used in fabrication of the jointed monolithic models. Three test specimens (152- by 152- by 533-mm prisms) were cast from each mixture. After the concrete was placed in the molds, the specimens were covered with a plastic sheet for approximately 24 hr. Bleed water was collected periodically from the concrete surface for the first few hours after casting until bleeding ceased. After approximately 24 hr, all specimens were covered with wet burlap. One specimen from each mixture was maintained in a moist state for the entire curing period of 6 days. One specimen from each mixture was maintained in a moist state for 5 days, and then the surface was allowed to air-dry for 24 hr. The remaining two specimens (one from each mixture) were maintained in a moist state for 5 days, the surface allowed to air-dry for 24 hr, and then remoistened. This simulated the curing conditions used in fabrication of the monolithic models except that the total curing time was shorter. Another difference was that the depth of the concrete in the test samples was less in this experiment than was the case in the monolithic models. This resulted in less bleed water on the surface of these smaller specimens than was evident on the lift surface of the larger models. After 6 days, samples were taken from the surface of the concrete specimens for examination by X-ray diffraction (XRD).

XRD patterns of the surface material from the plain concrete and the concrete with silica fume are given in Figures 4 and 5, respectively.

### **X-ray diffraction methodology**

In preparation for XRD examination, a sample was scraped off the surface of each prism and ground in a mortar and pestle to pass a 45- $\mu$ m sieve. XRD patterns were collected from these powdered samples using standard techniques for phase identification. The equipment used in this analysis was a Philips PW1800 Automated Powder Diffractometer system. The examination conditions included use of  $\text{CuK}\alpha$  radiation and step-scanning from 2 to 65° 2 $\theta$ , 8 seconds per step, and 0.05° per step with collection of the diffraction

patterns accomplished using PC-based windows 95 versions of Datascan (Materials Data, Inc.) and analysis using Jade.

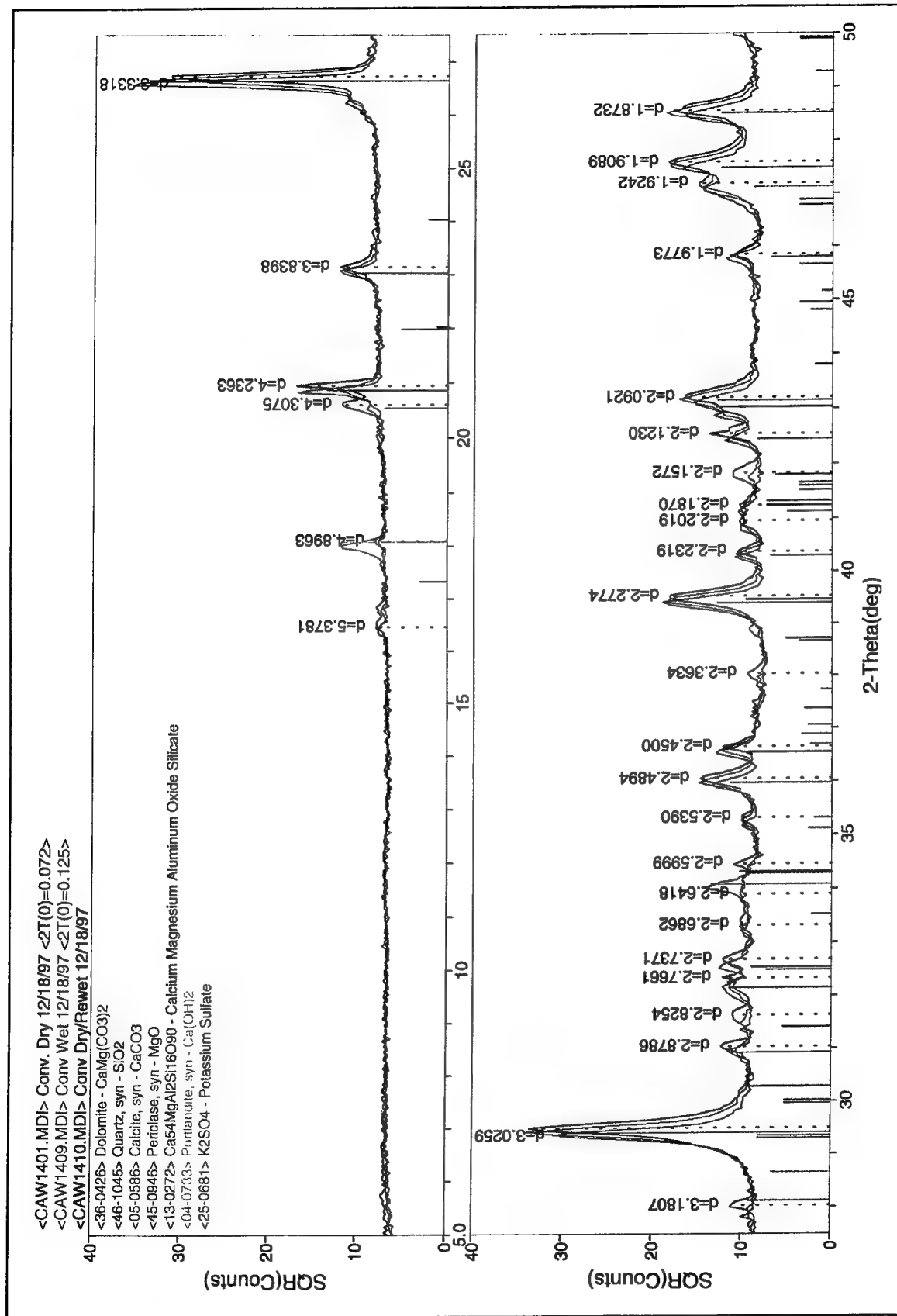


Figure 4. X-ray diffraction patterns of samples of concrete without silica fume removed from the top surface of concrete 7 days after casting

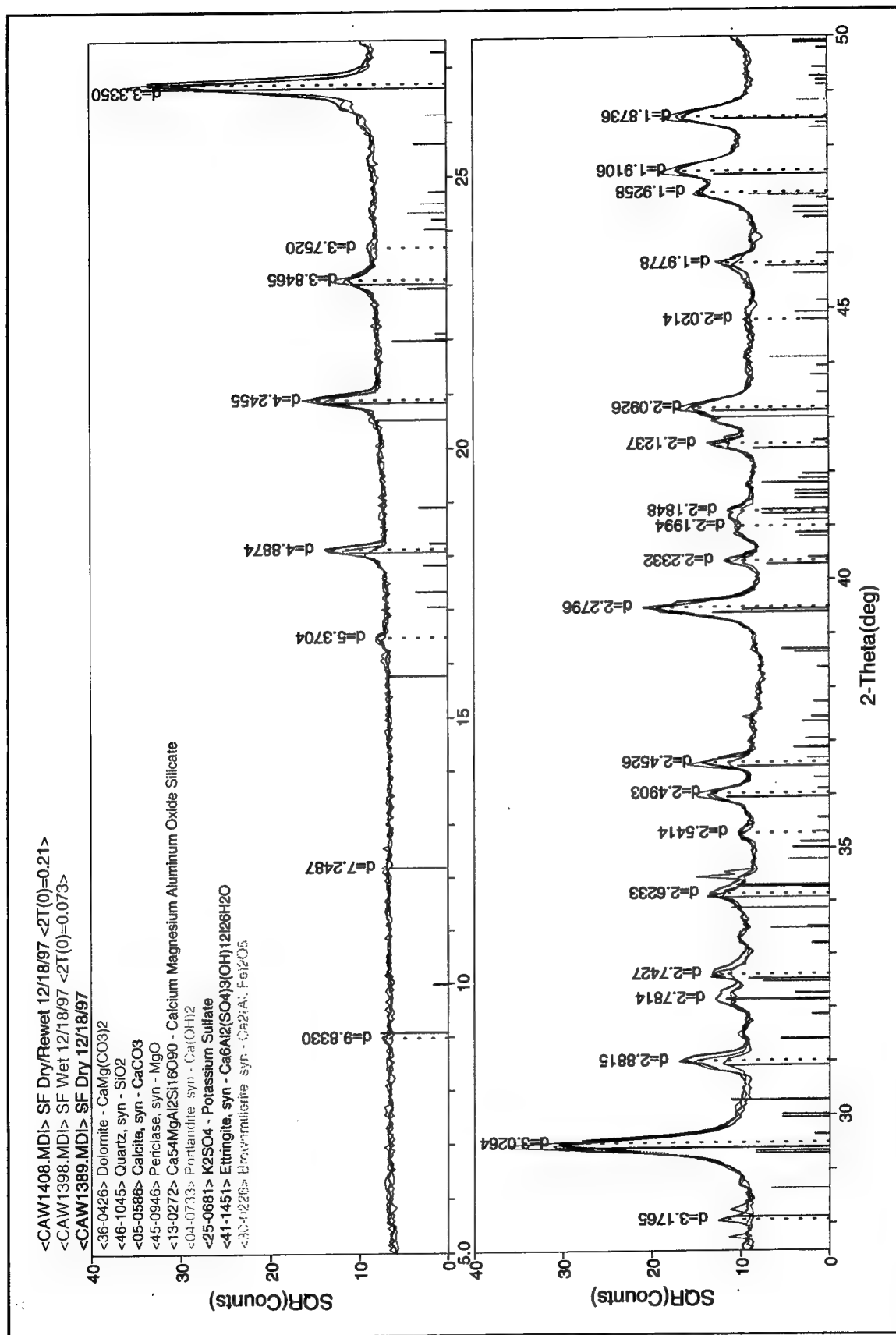


Figure 5. X-ray diffraction patterns of samples of concrete containing 2.5 mass percent silica fume removed from the top surface of concrete 7 days after casting

### 3 Test Results and Statistical Analysis

#### Direct Tensile Strength

Descriptive statistics of test results of direct tensile-strength testing are presented in Table 8. The results from this investigation are compared with the results reported in Neeley and Poole (1996) in Figure 6. Strengths for the condition in which the surface was dried for 24 hr then rewetted immediately prior to placing the second lift could not be determined because they were too weak to survive the coring procedure. Statistical significance of difference can be approximately judged using the standard errors as a measure. If the standard errors of two means do not overlap, then the differences are probably significant. This shortcut may not strictly apply with small data sets. Critical comparisons are made with Student's t-Test. Mean direct tensile strengths were not statistically different between the wet and dry surface conditions ( $t = 1.35$ , 10 d.f.,  $P = 0.21$ ). Relative to the tensile strengths for cleaned surfaces reported in Neeley and Poole (1996), tensile strengths for the joints in this experimental program were quite low, apparently lower than the values reported in the earlier study for the no-joint-treatment condition where considerable loose, flaky laitance had accumulated.

**Table 8**  
**Direct Tensile Strength (kPa)**

Block	Moisture Condition	Property	Type of Specimen	
			Joint	Intact
M	Continuously wet	Tensile strength, kPa Std dev Number of specimens	131 71 6	1,759 <sup>1</sup> 265 71
O	Dry 24 hr before 2nd lift	Tensile strength, kPa Std dev Number of specimens	85 43 6	

<sup>1</sup> Taken from Neeley and Poole, TR SL-96-2, p 12 (Neeley and Poole (1996)).



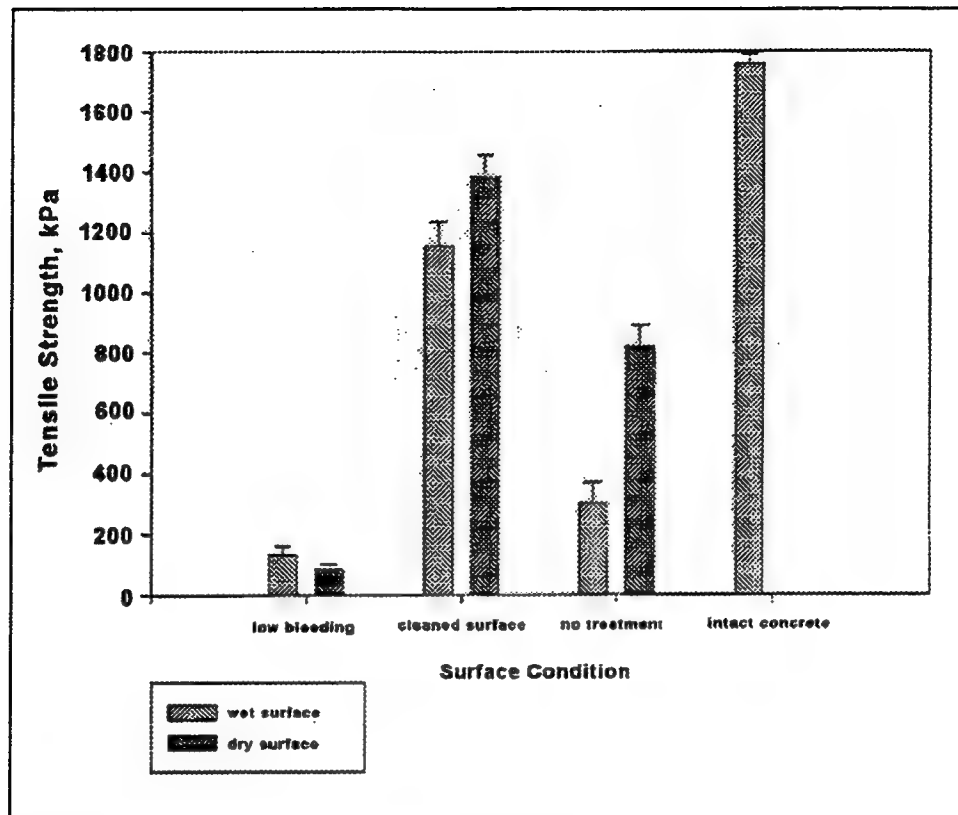


Figure 6. Comparison of direct tensile strength of joints in low bleeding concrete with tensile-strength data from jointed specimens reported in Neeley and Poole (1996)

Since the means for wet and dry conditions were not different, data were pooled, giving a mean tensile strength of 108 kPa, which was compared with the no-surface-treatment tensile strengths by Student's *t* Test. This value is lower than the 300 kPa value for the wet surface, no cleanup condition ( $t = 3.49$ , 15 df,  $P < 0.01$ ) and lower than the 820 kPa value for the dry surface, no cleanup condition ( $t = 12.97$ , 15 df,  $P < 0.001$ ).

## Shear Strength

### Maximum

Descriptive statistics of test results are in Table 9, and the comparisons with previously reported values are illustrated in Figure 7. Failure envelopes are shown in Appendix B. Maximum shear strength of the continuously wet condition was higher than the dry condition ( $t = 4.89$ , 6 df,  $P < 0.01$ ). Cohesion for the wet condition is comparable with values observed when surfaces were cleaned, as reported in Neeley and Poole (1996). The shear

Table 9 Maximum Shear Strength (kPa)				
Block	Moisture Condition	Property	Type of Specimen	
			Joint	Intact
M	Continuously wet	Cohesion, kPa Std error <sup>1</sup> , kPa $\phi$ , rad	3,405 320 0.96	4,791 606 0.16
O	Dry 24 hr before 2nd lift	Cohesion, kPa Std error <sup>1</sup> , kPa $\phi$ , rad	1,332 507 1.33	4,707 319 0.68

<sup>1</sup> Standard error of the intercept of the regression of shear stress on normal stress.

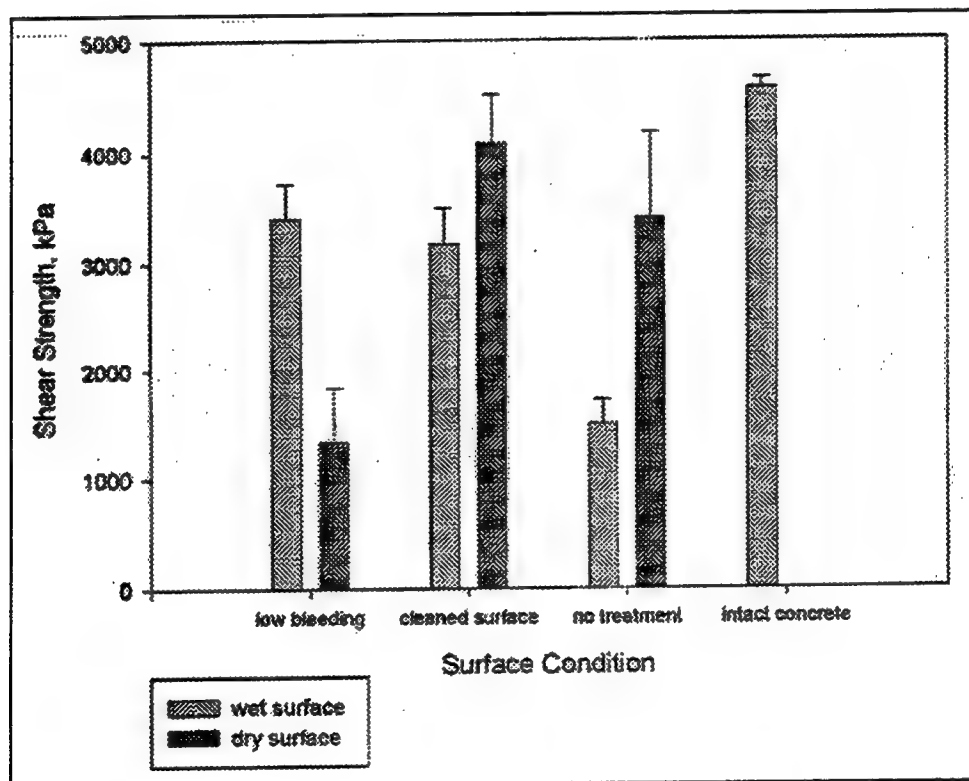


Figure 7. Comparison of maximum shear strength of joints in low bleeding concrete with tensile-strength data from jointed specimens reported in Neeley and Poole (1996)

strength of the dry condition was relatively low and similar to strengths of the no-joint-cleanup, continuously wet condition reported previously. This was concluded to be the worst condition in that work. The higher strength of the continuously wet condition relative to the dry condition found in this work is in reverse of the result observed in the previously reported work.

The coefficient of internal friction ( $\phi$ ) for the wet surface condition (0.96) was not significantly different from the mean value for jointed specimens reported in Neeley and Poole (1996) of  $0.86 \pm 0.12$  (95-percent confidence interval), as judged by inspection of standard errors.  $\phi$  for the dry condition was 1.33. The standard-error range taken from the linear regression calculation is from 1.27 to 1.38, suggesting that this test result is actually different from the  $\phi$  of 0.86 reported from other test conditions.

## Residual

Descriptive statistics of test results on residual cohesion values and  $\phi$  angles are summarized in Table 10, and comparisons of mean strengths are illustrated in Figure 8. Failure envelopes are given in Appendix B. The residual shear for the wet condition (76 kPa) was not significantly different from zero ( $t = 0.245$ , 3 df,  $P = 0.882$ ). The residual shear strength for the dry condition (156 kPa) was significantly different from zero ( $t = 4.554$ , 3 df,  $P = 0.045$ ). The value of  $\phi$  for both moisture conditions was significantly different from the value of  $0.70 \pm 0.03$  (95 percent CI) reported in Neeley and Poole (1996) for jointed specimens. The value for the wet condition was higher (0.97), and it was lower (0.59) for the dry condition.

Table 10 Residual Shear Strength (kPa)				
Block	Moisture Condition	Property	Type of Specimen	
			Joint	Intact
M	Continuously wet	Cohesion, kPa Std error <sup>1</sup> , kPa $\phi$ , rad ( $\pm$ s.e.)	76 311 0.76 (1.12-0.88)	
O	Dry 24 hr before 2nd lift	Cohesion, kPa Std error <sup>1</sup> , kPa $\phi$ , rad ( $\pm$ s.e.)	156 34 0.56 (0.64 - 0.53)	30 183 1.01
<sup>1</sup> Standard error of the intercept of the regression of shear stress on normal stress.				

## Drying Shrinkage

Results of the drying shrinkage measurements from unrestrained prisms (76- by 76- by 254-mm) are shown in Figure 9. Only minor differences existed between the two concrete mixtures. The water-to-cementitious-materials ratios, the water contents, and the aggregate volumes were nominally the same for both mixtures. The primary difference between the two mixtures was the presence of silica fume as 2.5 percent by volume of total cementitious material in one mixture. The silica fume modifies the hardened cementitious

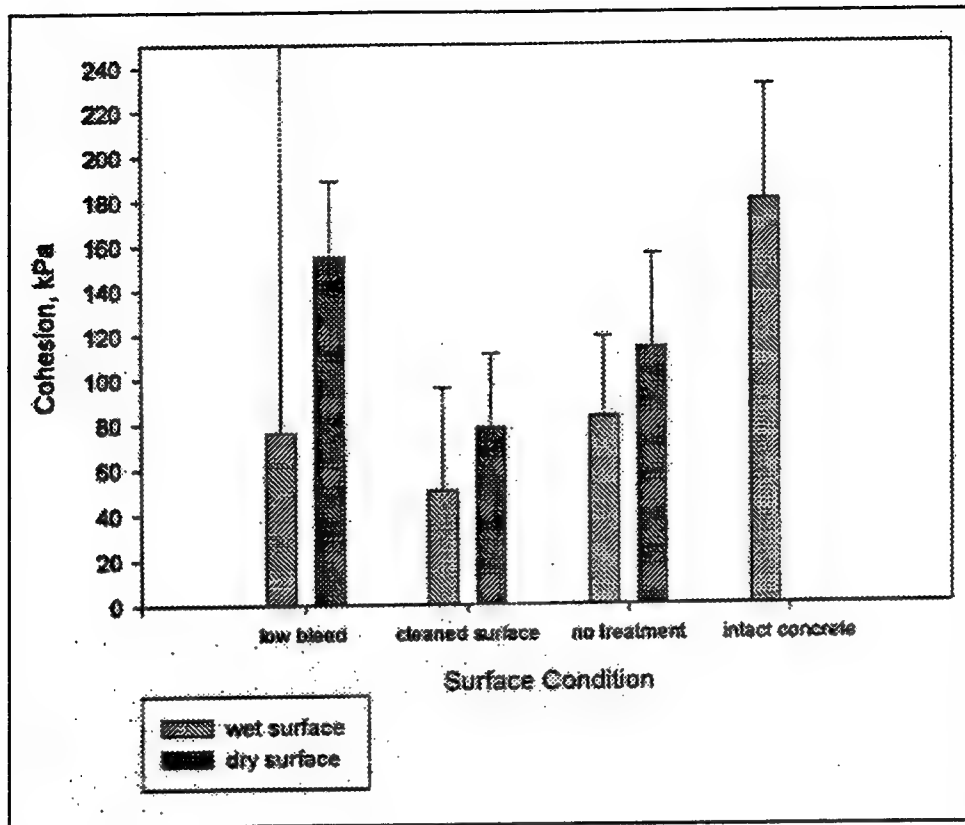


Figure 8. Comparison of residual shear strength of joints in low bleeding concrete with tensile-strength data from jointed specimens reported in Neeley and Poole (1996)

material paste to the extent that it should be somewhat denser than that of the mixture without silica fume. Therefore during water curing, less water will be absorbed by the cement gel leading to less swelling. This is supported by the data shown in Figure 7. The mixture with silica fume exhibits less expansion during the first 28 days of curing at 100-percent relative humidity. Once the concrete was placed in an environment of  $50 \pm 4$ -percent relative humidity, the rate of shrinkage appears to be equal.

It has been shown (Malhotra et al. 1987) that higher amounts of silica fume, i.e., 30 percent by volume, can significantly increase the shrinkage potential of paste. It was suggested that this increase in drying shrinkage could be related to the greater amount of C-S-H per volume of material and that no  $\text{Ca(OH)}_2$  was present to restrain the material during drying. It would appear that the addition of silica fume in small quantities (2.5 percent by volume) does not cause a complete depletion of  $\text{Ca(OH)}_2$  as when larger quantities of silica fume are present. Further restraint provided by densely packed aggregate particles results in a concrete that has shrinkage characteristics similar to that when no silica fume is present.

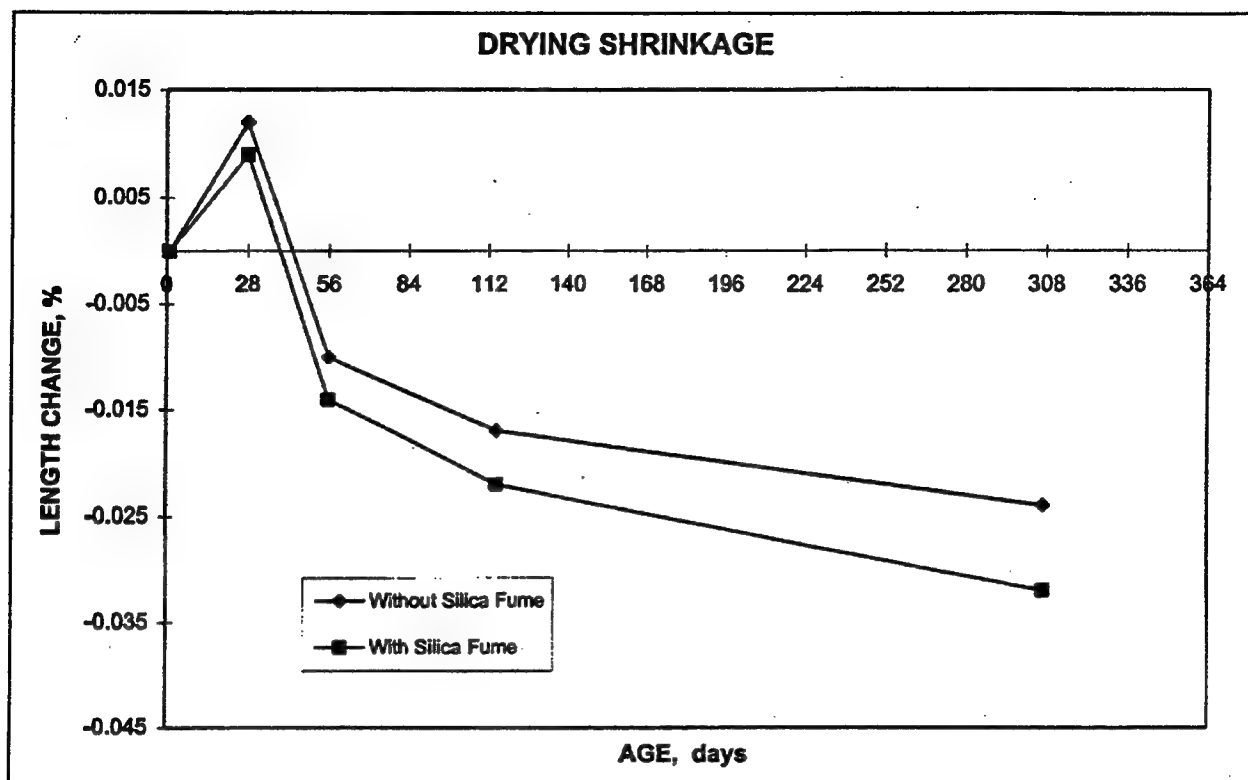


Figure 9. Measurements of drying shrinkage from unrestrained prisms

## Examination of Surface Material

XRD patterns of the three samples of plain concrete with the different curing conditions (labeled dry, wet, and dry and rewet) are given in Figure 4. The phases (as indicated on the bottom of Figure 4) present include unreacted cement, minerals from the coarse and fine aggregate (calcite [ $\text{CaCO}_3$ ], dolomite [ $\text{CaMg}(\text{CO}_3)_2$ ], and quartz [ $\text{SiO}_2$ ]), and reaction products due to the hydration of the portland cement (portlandite [ $\text{Ca}(\text{OH})_2$ ]). The unreacted portland cement (dominated by alite and belite, nominally  $\text{Ca}_3\text{SiO}_5$  and  $\text{Ca}_2\text{SiO}_4$ , respectively) has its major diffraction peaks at  $\sim 0.279 \text{ nm}$  ( $2.79 \text{ \AA}$ ) and  $\sim 0.276 \text{ nm}$  ( $2.76 \text{ \AA}$ ). Phases found in the unhydrated portland cement that were also observed include periclase [ $\text{MgO}$ ] and  $\text{K}_2\text{SO}_4$ . The samples of concrete without silica fume contain approximately the same amount of each phase with the exception that the amount of portlandite present in the wet and dry and rewet samples was much lower than that of the dry sample. This can be observed by the peaks at  $\sim 0.49 \text{ nm}$  ( $4.9 \text{ \AA}$ ) and  $\sim 0.264 \text{ nm}$  ( $2.64 \text{ \AA}$ ) for portlandite in Figure 4. It is also noted that the potassium sulfate, although a trace phase in all samples, is highest in the sample that was allowed to dry and then rewet.

XRD patterns of the three samples of concrete with silica fume added for the different curing conditions (labeled dry, wet, and dry and rewet) are given in Figure 5. The phases (as indicated on the bottom of Figure 5) present

include the same phases indicated in Figure 4 except for the presence of ettringite  $[\text{Ca}_6\text{Al}_2(\text{SO}_4)_3(\text{OH})_{12} \cdot 26 \text{H}_2\text{O}]$  and brownmillerite  $[\text{Ca}_4\text{Al}_2\text{Fe}_2\text{O}_{10}]$ . Brownmillerite is a phase present in the unhydrated cement, and the ettringite is a phase formed during the hydration process. The samples of concrete with silica fume added contain approximately the same amount of each phase with the exception that the amount of portlandite present in the dry and rewet sample was much lower than that of the wet and dry samples.

## 4 Discussion of Results

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### Bleeding and Laitance

Shortly after placement of the bottom lift of concrete (with silica fume), some bleed water did appear on the surface. This was not surprising given the small amount of silica fume. However, the intent was not to eliminate bleeding altogether, but rather to minimize the accumulation of loose, flaky laitance. An examination of the hardened surface prior to placement of the top lift revealed that no loose, flaky laitance was readily visible (Figures A1 through A6). While the bottom lift of concrete did bleed, indications are that the silica fume minimized the bleeding sufficiently to prevent the accumulation of loose, flaky laitance on the surface after hardening. However, as is characteristic of many silica-fume concretes, the hardened surface had a smooth, somewhat glassy appearance. Indications are that this smooth, somewhat glassy surface prevented the formation of a strong bond.

### Joint Strength

The results reported in Neeley and Poole (1996) appeared to be internally consistent in describing patterns of the effects of moisture condition and type of surface cleaning on physical properties of a construction joint. In general, that work concluded that surface cleaning was important, but that cleaning to the point of undercutting aggregate was not necessary or desirable, and that dry surfaces tended to give stronger bonds across the joint than did wet surfaces. The results reported in this work appear not to agree with the pattern described in the earlier work. Apparently, the presence of the silica fume in the mixture created a surface condition unlike the surface condition that existed in the concretes used in the first study. It is clear that using silica fume for the purpose of minimizing bleeding so as to avoid the need for surface cleaning between lifts was not successful. The results obtained in this work raises the question of whether silica fume concretes in general respond to the surface treatments in the same way as concretes without silica fume or whether a different pattern exists.

One source of caution in interpreting the results of this work is that each surface preparation and moisture condition combination was represented by only one test block. The replication that was used for statistical analysis reflected variation among the cores taken from that single block. So, if there was some unusual but unknown feature about the preparation of one of the test blocks that was unrelated to the principal variables of interest, then spurious conclusions could be drawn from the statistics. However, the interpretation of strength results generally does not depend critically on results from one block and therefore is reasonably robust with respect to this sampling problem.

One other source of caution in interpreting the results of this work is the reference to "dry" surfaces. None of the surfaces described as "dry" were exposed to high temperatures and low relative humidities for relatively long periods of time, as might occur in construction. No "dry" surface was allowed to dry at a temperature greater than approximately 30 °C, or at a relative humidity lower than approximately 40 percent, nor for a time greater than 24 hr. Hence, if one wishes to get the performance described herein as obtained with "dry" surfaces and the actual surfaces are drier than described above, they should be rewetted and allowed to dry no more than described. It should also be noted that all the concrete used in these tests had 100 kg of water per cubic metre of concrete or a water-cementitious material  $w/(c+m)$  ratio of 0.55 by mass. If a lower water content or lower  $w/(c+m)$  concrete were used, there might be very little continuous capillary space in the paste. Therefore, loss of water from the near surface of the lower lift would be difficult to achieve and to replace. A concrete of  $w/(c+m) = 0.55$  will have no capillary continuity after approximately 6 months, but one of 0.4  $w/(c+m)$  can lose capillary continuity in approximately 3 days of moist curing.

## Surface Material Mineralogy

### Concrete with silica fume

These samples subsequent to placement did appear to have less bleed water on the surface than did the samples with the plain concrete. However, as is characteristic of many silica fume concretes, the hardened surface had a smooth, somewhat glassy appearance that was not observed on the surface of the concrete without silica fume. This smooth, somewhat glassy appearance was less evident on the surface of the sample that was maintained in a moist condition for the entire curing period.

X-ray diffraction patterns of material removed from the surface after the end of the curing period show calcium hydroxide is still present. This indicates that the level of silica fume was insufficient to react with all of the calcium hydroxide. The weak bond measured on the joints that were allowed to dry may be the result of an accumulation and crystallization of fine-grained material (either unreacted silica fume, calcium hydroxide, or calcium silicate



hydrate) on the surface. The stronger bond measured on the joints that were maintained in a moist condition for the entire curing period may be the result of less accumulation and crystallization of the fine-grained material on the surface.

#### **Concrete without silica fume**

X-ray diffraction patterns of material removed from the surface after the end of the curing period show less calcium hydroxide on the samples that had been kept continuously moist or remoistened after drying than was indicated on the sample that was allowed to dry and was not rehydrated. Apparently, the water caused the calcium hydroxide to dissolve on the surface of the concrete. The weaker bond measured on the joints that were maintained in a moist condition or rehydrated after drying may be the result of dissolved calcium hydroxide on the surface. The formation of calcium hydroxide on the surface during hydration of the portland cement and subsequent drying of the surface did not appear to hamper the formation of a strong bond.

## 5 Conclusions and Recommendations

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### Conclusions

The concrete mixtures used in this program contained a mortar content within the range recommended by ACI 211.1, "Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete" (ACI 1996), for concrete mixture containing 75-mm NMS aggregate. The mortar content was sufficient to fill voids between the coarse aggregate particles and the voids in the prepared lower surface.

The use of a small quantity of silica fume does appear to minimize the amount of bleeding and resulting loose flaky laitance. However, without any cleaning of the surface, freshly placed concrete may not adequately bond to the existing surface. Under some circumstances, the solid laitance that does form on the concrete containing silica fume may actually inhibit bond more than the loose flaky laitance that forms on the surface of concrete that does not contain silica fume.

Silica fume was the only mechanism examined in this study to minimize bleeding and resulting laitance. While other options could be explored, the addition of a small quantity of silica fume does not appear to be a viable option.

### Recommendations

CWGS-03305, "Mass Concrete" (Headquarters, Department of the Army 1992) states "Concrete surfaces to which concrete is to be bonded shall be prepared for receiving the next lift or adjacent concrete by cleaning by sandblasting, high-pressure water jet, or air-water cutting...Regardless of the method used, the resulting surface shall be free from all laitance and inferior concrete so that clean, well-bonded coarse aggregate particles are exposed uniformly over the lift surface. Application of the joint treatment method shall be such

that the edges of the larger particles of aggregate are not undercut.” The test results described above support this guidance, and no change is recommended, other than inserting “visible” before “laitance” since removal of laitance can only be to the extent it can be seen.

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  - g. Designation C 143-90. "Standard test method for slump of portland cement concrete."
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# **Appendix A**

## **Photographs of Joint Surfaces Prior to Placement of Second Lift**

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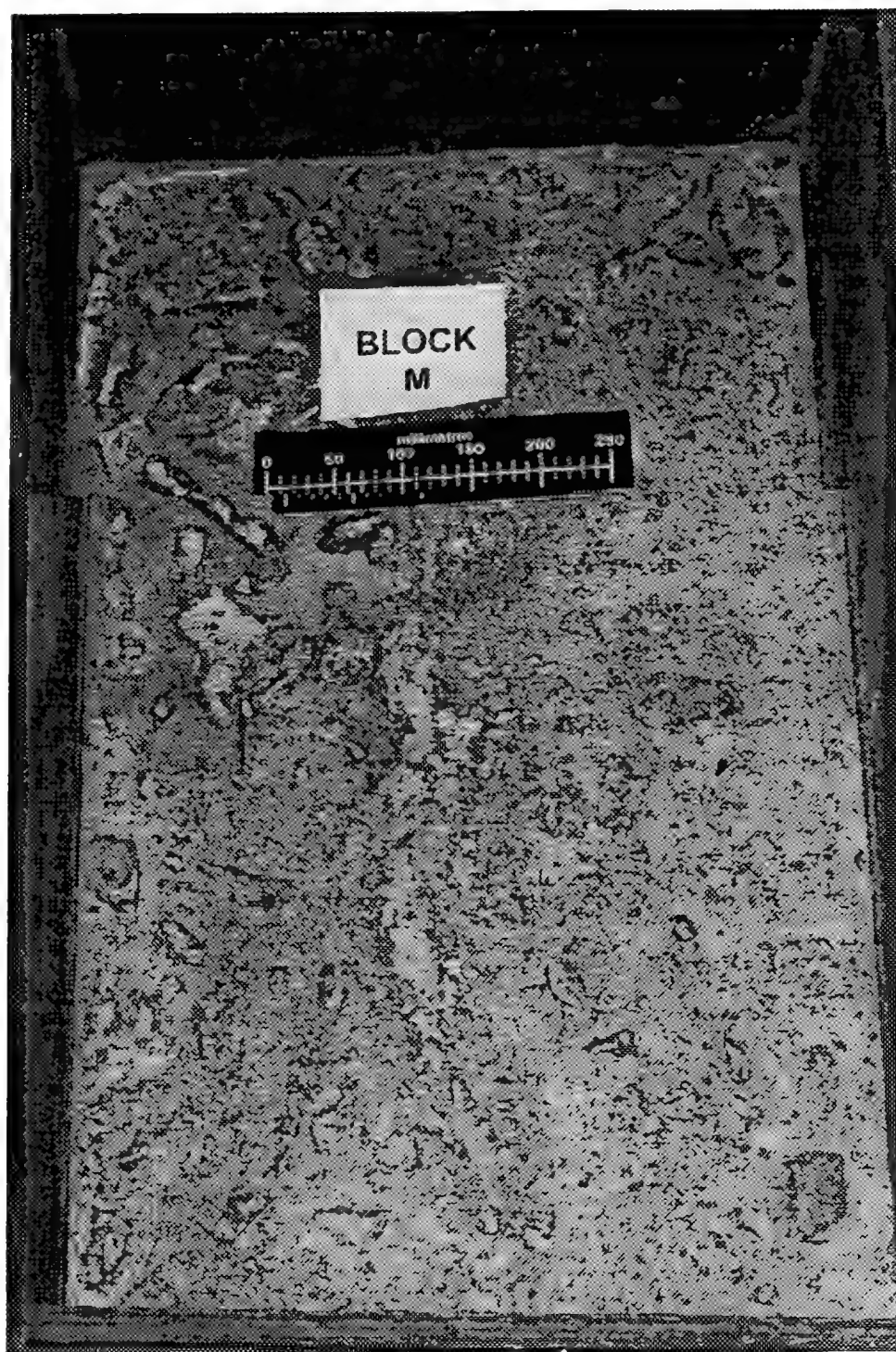


Figure A1. Joint surface of Block M, no joint cleanup, continually wet



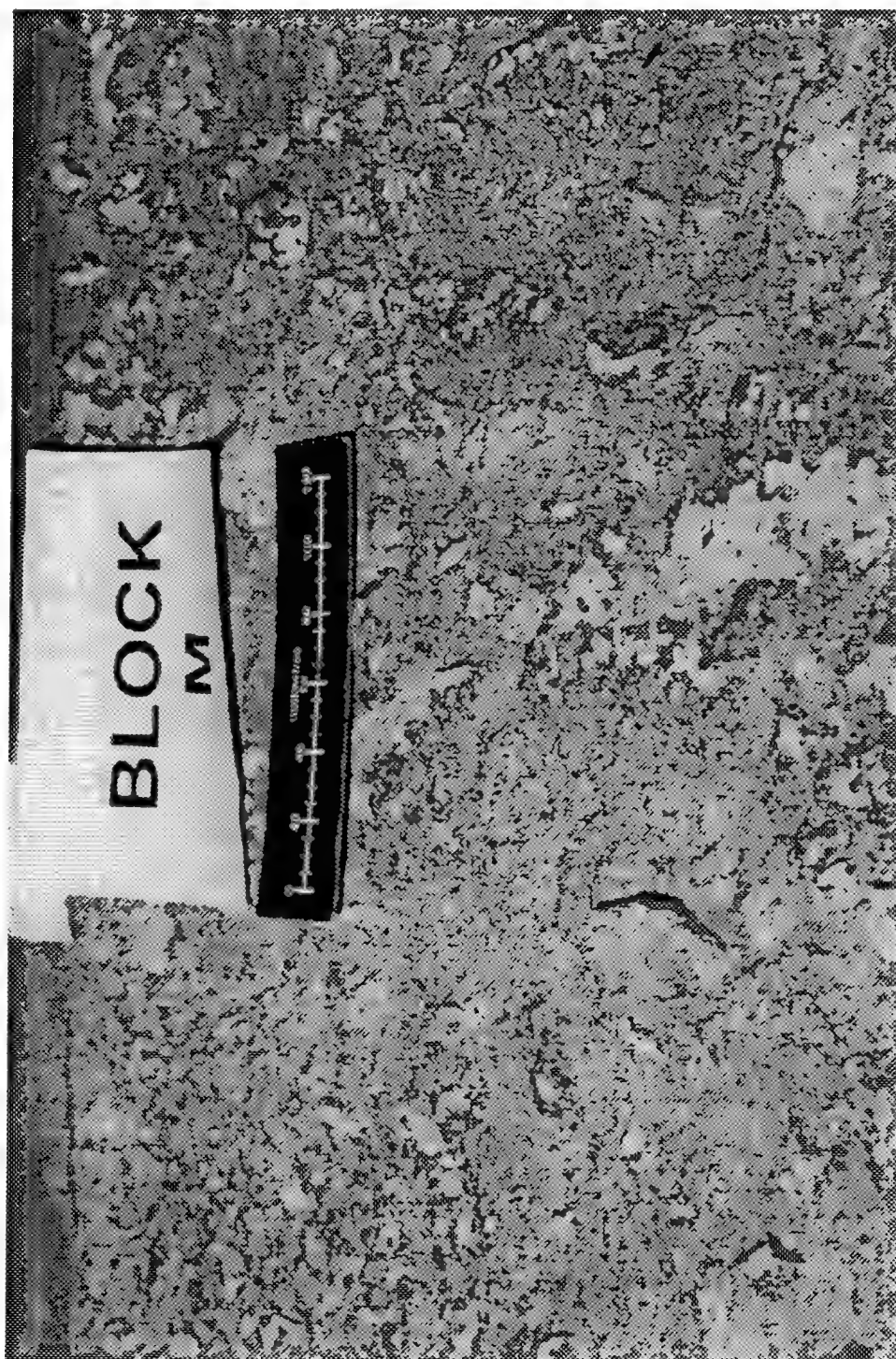


Figure A2. Close-up of joint surface of Block M, no joint cleanup, continually wet

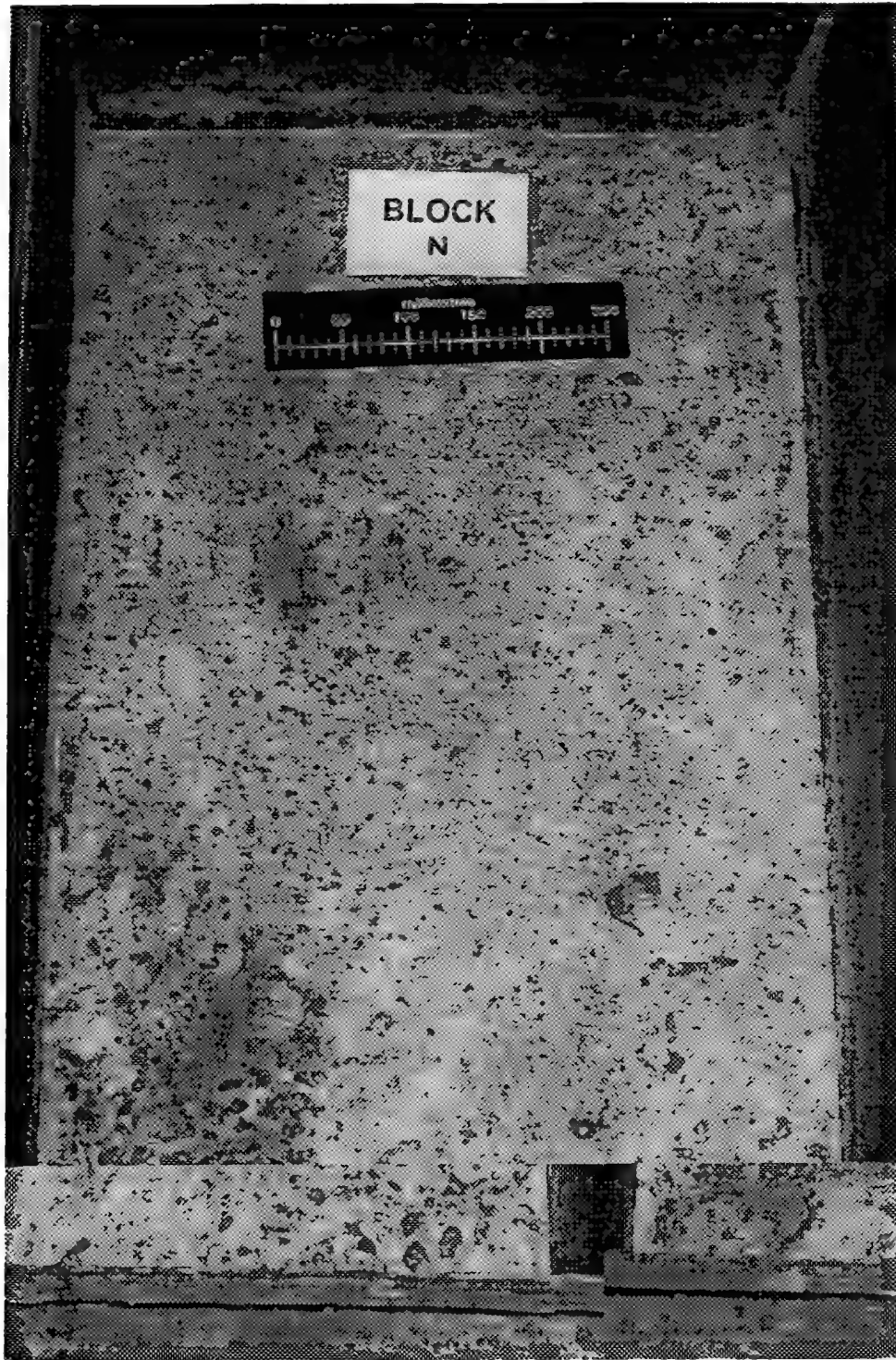


Figure A3. Joint surface of Block N, no joint cleanup, dry then remoistened

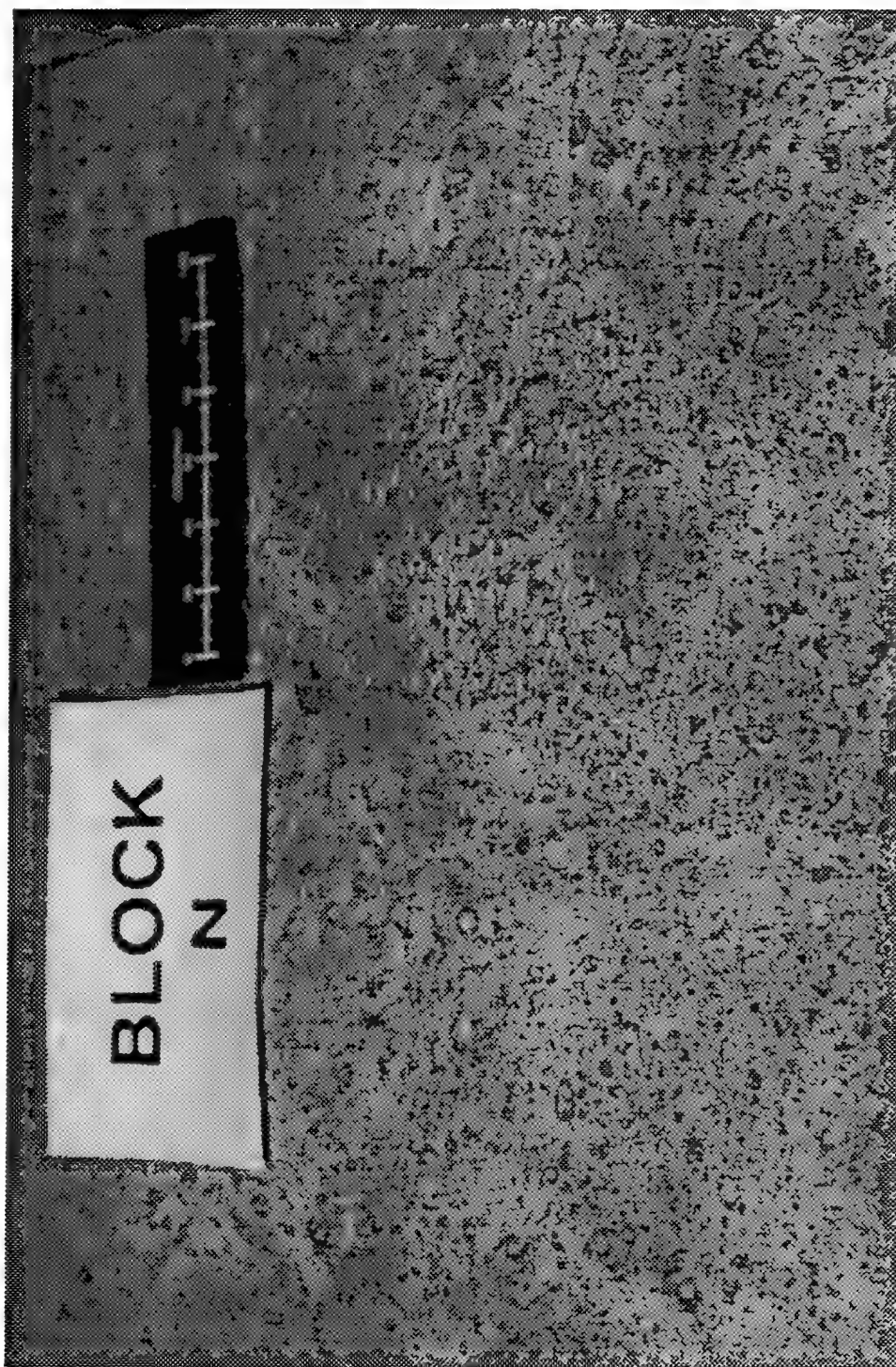


Figure A4. Close-up of joint surface of Block N, no joint cleanup, dry then remoistened





Figure A5. Joint surface of Block O, no joint cleanup, dry



Figure A6. Close-up of joint surface of Block O, joint cleanup, dry

# **Appendix B**

## **Failure Envelopes from Shear Tests**

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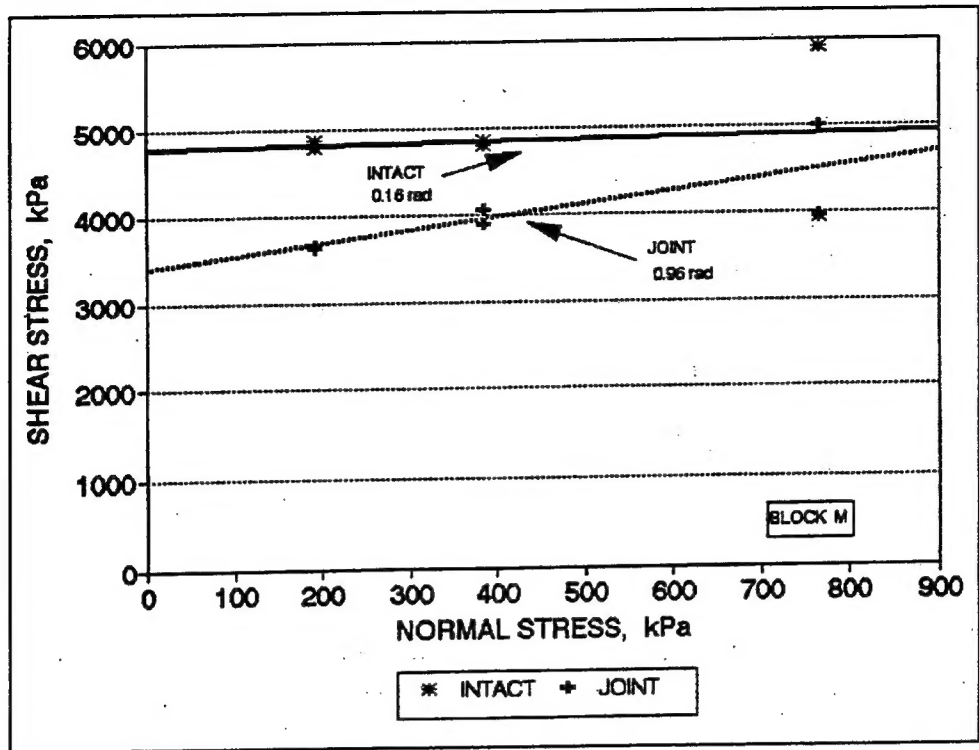


Figure B1. Maximum shear stress failure envelope, Block M, no joint cleanup, continually wet

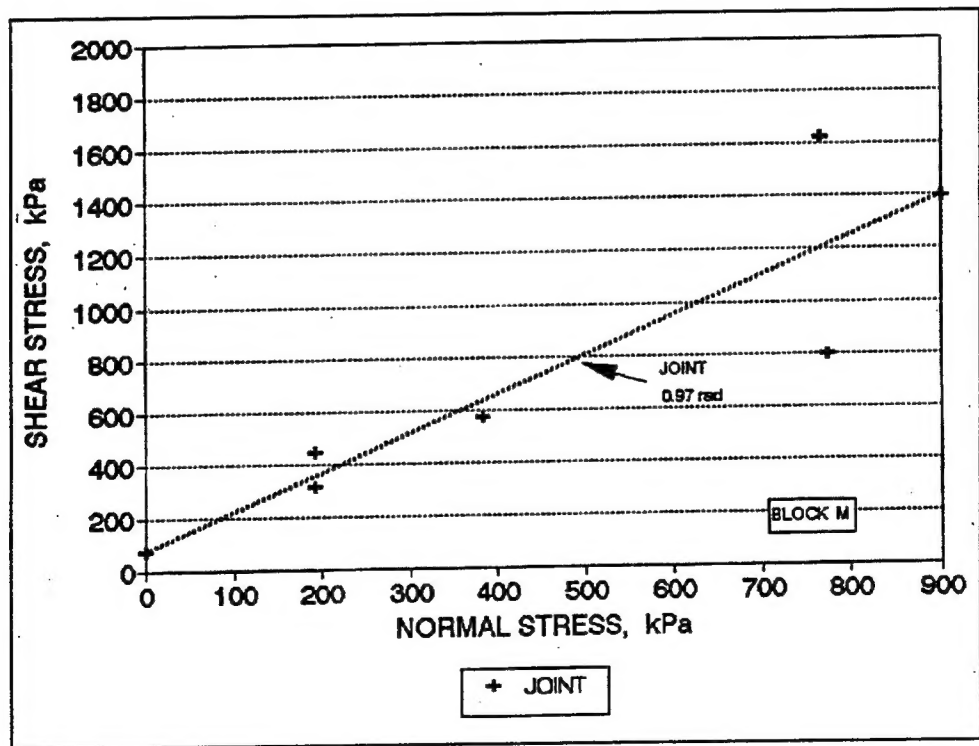


Figure B2. Residual shear stress failure envelope, Block M, no joint cleanup, continually wet

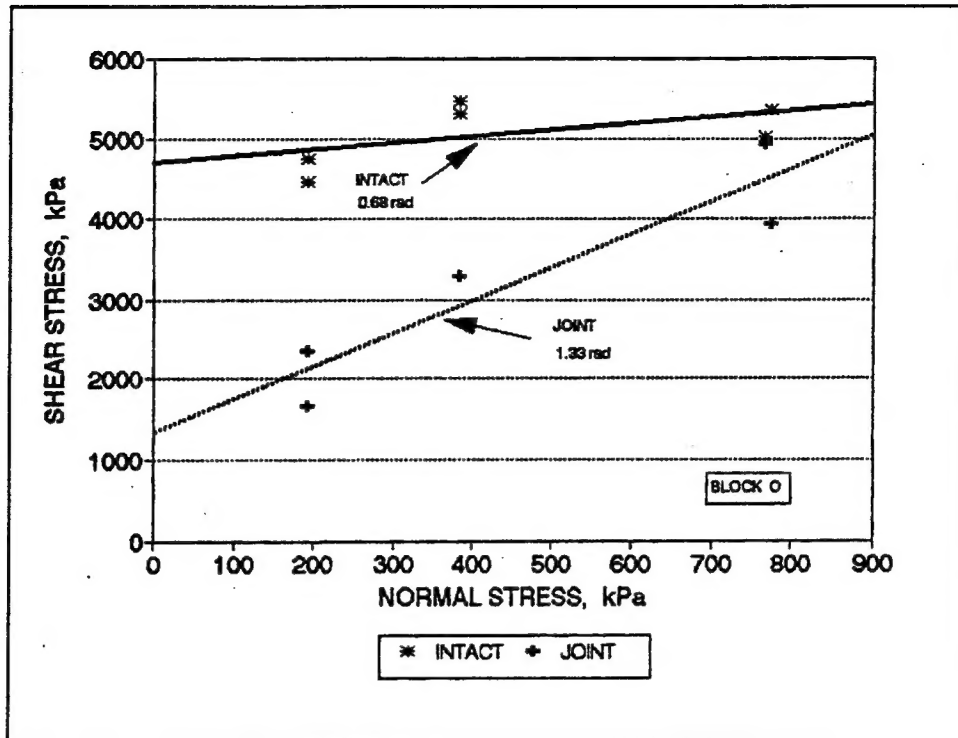


Figure B3. Maximum shear stress failure envelope, Block O, no joint cleanup, dry

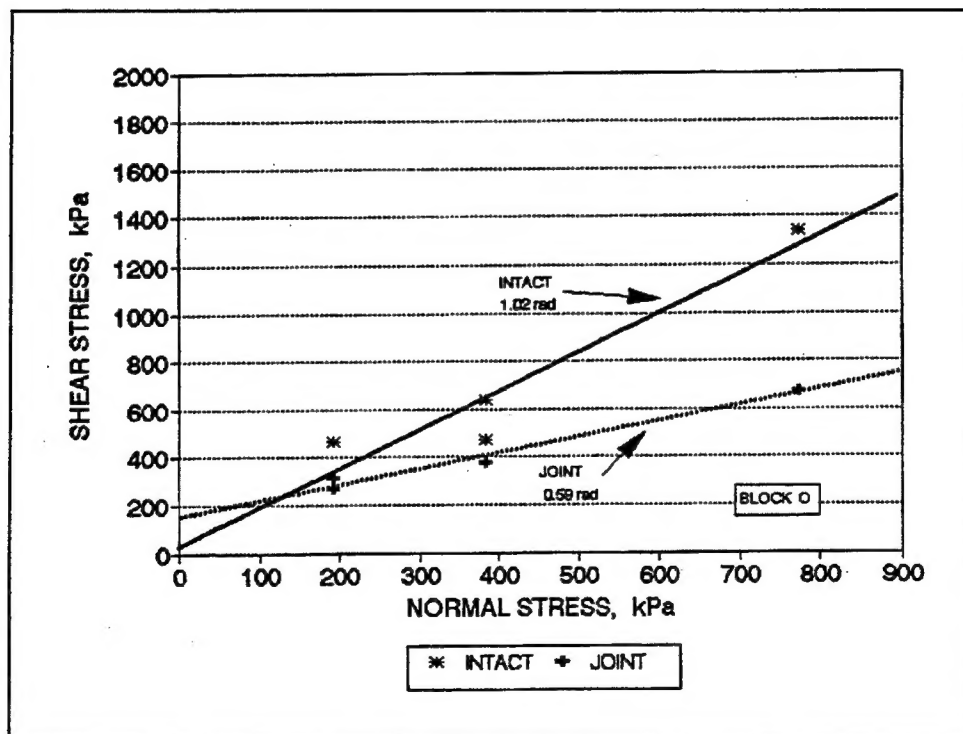


Figure B4. Residual shear stress failure envelope, Block O, no joint cleanup, dry



# REPORT DOCUMENTATION PAGE

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13. ABSTRACT (Maximum 200 words)  This report presents the results of a research program examining the effects of different methods of preparing horizontal construction joints in mass concrete construction. The purpose of the research program was to confirm existing guidance or, if necessary, update it. This is the second and final report. The joint moisture conditions at the time of concrete placement were (a) continuously moist, (b) dry, and (c) dry and then remoistened. There was no cleaning of the joint surface prior to placement of a second lift. The concrete mixture used in the first lift was proportioned to minimize bleeding and the resulting laitance. Jointed specimens were tested for direct tensile strength and shear strength. The results indicated that an addition of a small quantity of silica fume does decrease bleeding and reduce loose, flaky laitance. However, a smooth, somewhat glassy surface appears to interfere with the bonding of the next lift of concrete. Bond strengths are not as good as those when the horizontal construction joints are cleaned by high-pressure water cutting or by air-water cutting, and then allowed to dry approximately 24 hr immediately prior to placement of the next lift of concrete. This technique is not recommended. Current guidance concerning joint cleaning procedures should be followed.					
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